A Model for Public-Private Sector Distribution Planning for the U.S. Coal Industry

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Keywords: linear programming; coal production; coal mining

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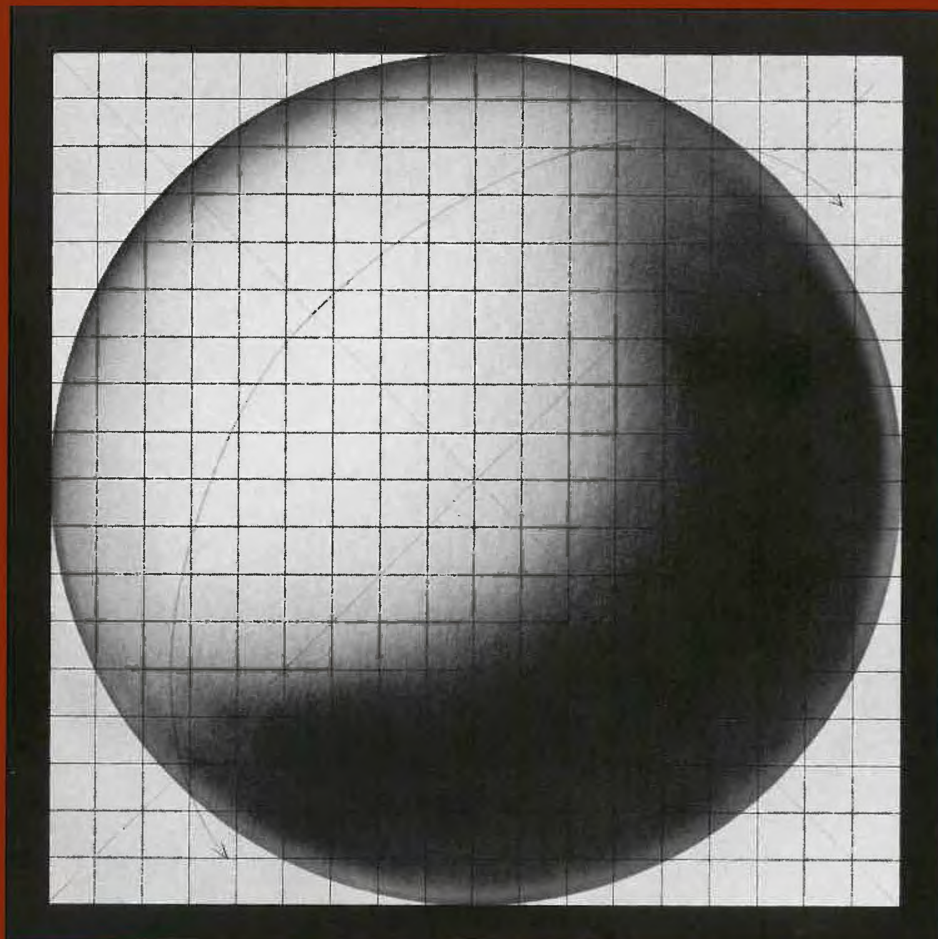

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A MODEL FOR PUBLIC-PRIVATE SECTOR DISTRIBUTION PLANNING FOR THE U.S. COAL INDUSTRY

by Fred Phillips

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ABSTRACT

A multiperiod mixed integer linear programming model is proposed as a guide to the urgent expansion of the production and interregional distribution of American coal. The model, run under various scenarios of resource costs and governmental restrictions, should serve as an indicator of the possible performance of the industry, a guide to effective legislation, and a program for optimal location and timing of mines and conversion and transportation facilities.

A mixed-integer linear programming model is presented which deals with distribution planning for the U.S. coal industry on an interregional scale, i.e. at a very high level of spatial aggregation. The intent is to study the sensitivity of the projected interregional coal flow patterns to the parameters of the industry's environment: principally, the costs of facilities, availability of machinery, and environmental and other legislation. The parameters themselves vary across regions and across time. The economic growth of individual regions, as well as the fortunes of the mining, transportation, and utility companies involved, depends upon these flow patterns and, by extension, upon the early recognition of the determinants of these patterns. The model presented here should therefore serve as a guide to effective internal industrial planning and well-considered legislation. For example, by incorporating the model's projections into regional input-output accounts and applying statistical hypothesis-testing techniques, the impact of a growing coal industry on a regional economy may be tested.

Technically, the mixed-integer programming model contains only a few 0-1 variables, and the cost structure associated with these variables may yield a meaningful solution via an ordinary LP algorithm. Furthermore, the constant conversion factor between tons and heat content for each grade of coal may make possible a transformation to or approximation by a network format.[1] Limited computational tests on example problems have been performed and will be described at the end of this report.

The multiperiod format of the LP model projects the time path of expansion of facilities. The model is deterministic, assuming perfect information at time t = 0 concerning the future of costs and environmental standards. The LP can be run under various scenarios, to indicate (a) the best performance of the industry under a set of economic and legislative conditions, and (b) those legislative actions which will elicit the best response from the industry. For example, one could test the consequences of the section in President Carter's energy plan which calls for stack scrubbers on all new coal-fired plants in order to encourage the use of high sulfur eastern coal and so boost employment in the East (Wall Street Journal, 14 June 1977). We feel our approach is reasonable because, firstly, those equipment costs not attendant upon technological breakthroughs may be reasonably well projected exogenously, and, secondly, it has been customary to set environmental standards as long-term schedules, rather than as piecemeal decisions over time. Given, as the editors of Coal Age observe, that uncertainty with regard to government actions is one of the industry's most serious problems, we believe the perfect information/scenario approach in which each scenario is a set of future cost and legislative parameters to be valuable because it is an effective means of testing the effects of the most imminent government actions as well as hypothetical government actions.[2] This approach is not expensive for an LP, and avoids the necessity of engaging in endogenous political or technological forecasting. Various horizon requirements (e.g. desired levels of assets or production at the planning horizon) may of course be appended to the multiperiod LP.

The model encompasses the industrial functions of location and timing of mines and facilities for conversion and transportation; choice of modes and routes of transportation; coal conversion via flotation cleaning, blending, or scrubbing (and possibly gasification or electrification); and the governmental functions of land lease control, environmental standards, and tax/subsidy. The objective functions must reconcile the interests of five groups: mining companies, transportation companies, utilities and other consumers, governments, and the public. Of course each of these contains disparate subgroups. (See Table 1.) Example problems were computed in a simple framework of cost-minimization or production-maximization. More sophisticated approaches might differentiate the industry and its environment via a game-theoretic or other multi-criterion optimization approach. Energy companies producing other fuels as well as coal will undoubtedly pursue a more complex policy than simple maximization of coal production.

In view of the nature of the current coal market, a contract-only market is assumed. The export and domestic markets for all types of coal are two-tier systems. Large producers and consumers cover their projected production and demand, as far as possible, by long-term coal contracts. Residual production, and the production of small mining companies, is sold or consigned to coal marketing companies who try to procure contracts for the sale of this coal.[3] The price of coal sold on contract is then fixed for the duration of the contract, although the contracts may be renegotiated in midterm. All coal not sold on contract, or otherwise reserved,

TABLE 1

COAL ENERGY INTEREST GROUPS & MAJOR TOPICS OF INTERACTION

	Coal Producers	Utilities, Industrial Consumers	Government	Public	Transportation
Coal Producers	Competition	Contract. Terms.	Leasing, Reclamation, Subsidies, Taxes, Depletion allowance, Depreciation.	Wilderness preservation. Mine health & Safety. Profits.	Loading & Interface, Ability to open mine. Cost structure.
Utilities Industry		Power supply & Industrial, Capitol investment.	Emissions standards. State of economy. Nationalization issue. Price control.	Profits. Price.	Demand affects new routes. Delivery agreements. Costs.
Government				Energy Policy Living Standard Employment GNP. Inflation Environmental policy. Public opinion.	Pipeline right of way. Environmental impact. Subsidies.
Public					Cost. Capacity. Environmental Preservation.
Transp.					

enters the so-called spot market and is sold (or not sold) at a price determined by current market conditions. The far greater volume of coal on the contract market, as well as the fact that the current state of the contract market yields more knowledge of the future than does the present state of the spot market, makes it more likely that transportation planning will be done on the basis of projected contract markets. Coal consumers who own "captive" mines presumably handle the attendant transportation planning internally, so long as the captive arrangement remains profitable.

The treatment of the coal industry as an undifferentiated entity is partially justified by the recognition of government, industry, and the public during this energy crisis, that extraordinary measures are necessary to save an energy-dependent economy, and that a willingness to temporarily alter the usual competitive processes may well be part of the solution. Although a variety of useful welfare measures suggest themselves, this paper does not contain a discussion of welfare related objective criteria for the model.

Of coal produced in the United States, 54% is consumed as fuel for electrical generation, both industrial and by utilities; 18% is used to produce industrial steam; 4% is used to produce various chemicals; and 24% is used to generate heat for industrial processes.[4] A fraction of the latter is of special types needed by the coking and cement industries and others.[5] All coal which is not coking coal, etc., is called "steam coal," and terms such as "anthracite," "lignite," and "bituminous" classify steam coal according to hardness and volatility. The LP model as described below deals explicitly with the most significant (in terms of volume) market, that for steam coal of varying heat and sulfur content. Coking coal and the like could be considered as well, if desired, with no change in the model's structure.

In 1973, coal shipments within the United States broke down as indicated in Table 2; the railroads' share alone generated $1.4 billion in revenues.[6]

Table 2

Modal Breakdown of U.S. Coal Movements, 1973

rail	67.1%
barge	11.6
truck	9.7
used at mine	0.7
conveyor or truck to minemouth generator	10.9

A 1975 study by the National Academy of Engineering concluded that rail/barge combinations will continue to dominate coal shipment in the East; in the West, unit trains will face increasing competition from slurry pipelines, which have lower costs and do not require empty return runs.[7]

The combustion of sulfur along with the coal that contains it, produces sulfur dioxide, a noxious chemical harmful to crops and animals. Sulfur dioxide not falling directly to the earth is absorbed by atmospheric water, and reappears as corrosive sulfuric acid.[8] For this reason, the heaviest emphasis in effluent standards for coal furnaces has been on sulfur emissions. The emission of ash and particulate matter is also of concern, and may be handled by a straightforward extension of this model.

The National Coal Association (N.C.A.) recognizes five basic ways to control sulfur emissions. These are (1) the use of low-sulfur fuels; (2) chemical removal of sulfur oxides after combustion; (3) removal of sulfur from coal prior to combustion; (4) "alternative controls," i.e. the combined use of tall stacks, careful air quality monitoring, computer simulation of weather, with production cutbacks when weather conditions would concentrate emissions; and (5) conversion of coal to gas, possibly underground.[9] The visible soot that was in the past associated with coal-fired plants was due to "fly ash." Modern electrostatic precipitators, the N.C.A. claims, can remove more than 97% of the fly ash from a plant's exhaust.[10]

The provisions of emission standards vary from state to state, and federal standards add another dimension of complexity. A sensible and common structure, though, is to scale the allowable output of sulfur (in pounds per million BTU of fuel input) to the output capacity of the plant (in megawatts).[11] Thus a larger plant must burn cleaner, pound for pound, than a smaller plant. A knowledge of the size and thermal efficiency of a given plant and of the sulfur content of its fuel enables us to express the allowable emission in terms of raw tons of coal input per year. The model currently assumes similar efficiency for like-size plants, resulting in a single standard for each size of plant in a given region and time period. Because the definition of plant classes within the model is arbitrary, it may be relaxed if this assumption is eventually found to be inadequate.

In general, Western coal (primarily from N. Dakota, Montana, Wyoming, Colorado, and Arizona) is of lower sulfur content but also of lower heat value by weight than Eastern coal, although there is much local variation in sulfur content even between different seams in a single mine.[12] The need to express energy output in common units makes it convenient to define demand in terms of BTU's per period.

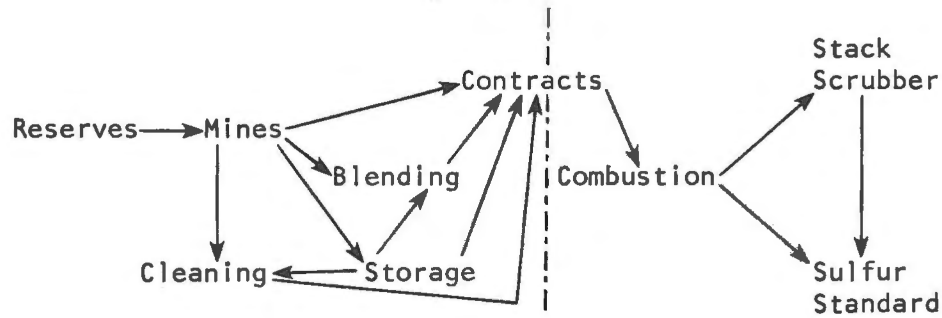
It has been common practice for a given power plant to be supplied exclusively, on a contract basis, by a single (either "captive" or contracted) coal mine.[13] In some cases, although it is not the rule, a single utility, which may consist of several plants, is the sole customer for a given mine's output. In such cases, the prior contract may have secured the initial financing for the mine.[14] For the purposes of the LP model, the "terms" of a contract are defined as (a) the lifetime of the contract (in time periods, denoted by the index τ), and (b) the agreed rate of delivery (in BTU's per time period, denoted by the index d). In practice, contracts may be frequently renegotiated--this is not a feature of the present model. It would be possible to approximately handle contract renegotiation by limiting the "lifetime" of a contract, τ, to the empirically determined "mean time to renegotiation" of a new contract. The post-negotiation remainder of the contract would then be regarded as a new contract, with the price level determined in the normal way by the dual LP variables. Bound constraints would ensure that the number of new contracts in period t be at least the number of contracts renegotiated in t-1.

The projected demand, as input to the model, is defined as the number of contracts of type (τ, d) to be expected to originate in each region i, in each period t. The number of contracts will depend partially on the obsolescence schedule of currently operating oil and gas burning furnaces owned by utilities, and on legislation requiring their conversion to coal fuel. The model determines which grades of coal may fulfill those contracts. If a contract calls for delivery of grade q coal, for example, the mining company may provide either direct-from-the-mine grade q coal, or upgraded (converted) coal of a lesser grade. If local air standards require at least q-grade emissions, the customer may burn grade q or may burn a lesser grade, and scrub the stack emissions up to the required quality, if technologically feasible. If the customer builds a stack scrubber at mid-contract, or if the miner's conversion facilities are expanded, the above pattern may be altered in midstream. Further characteristics of the coal industry, particularly having to do with "conversion" processes, will be noted as the model's variables are defined below.

The interregional coal flows in any period depend on the delivery commitments from all outstanding contracts. (The determination of flows through a transportation network with transshipment, <u>where contracts exist</u>, poses a special and interesting new computational problem. See Appendix.) These deliveries (of possibly converted coal) must conform to air standards. Thus the origin of a ton of coal must not be "forgotten" by the model even after it leaves the conversion facility.[15] Multiple subscripts are therefore necessary to index the origin, intermediate conversions, and destination of all shipments because a given shipment may undergo more than one conversion and travel by different routes and modes.

In each period we may conceive of the network of Fig. A 1, showing the technological interaction between a pair of regions:

Fig. A 1



The broken line symbolizes the regional boundaries and the figure summarizes the technological structure of the model. Some features to be noted are: (a) sulfur standards are regionally and temporally variable; (b) a cleaned product may be input to a blending process, but not vice-versa; (c) cleaning, storage, and blending are assumed to occur in the region of origin; and so on.

Indices used as sub- and superscripts are now defined:

i origin region of a coal shipment, or region in which a mine is located; also, for formal purposes, the location of a contracted supplier.

j destination region for coal shipments; source region for coal contracts; location of the customer.

k or k' the site of a conversion process (within an origin region i), which belongs to a set of conversion processes K or K'.

"Conversion processes" are defined very broadly here, and the notation will require some explanation. Conversion processes are taken to include mining (extraction; interperiod storage; flotation cleaning; blending for a size d customer in region j(i); and shipment without further conversion to a size d customer in region j(i). j(i) denotes a consuming region bound by contract with region i, and ranges from 1 to J(i) for every i. Consequently there are 2 x J(i) + 3 possible elementary conversion processes associated with each source region i.

The set K (or K') of conversions has elements k (or k') which represent individual conversions as set forth above, or sequences of conversions. For example, constraint B below operates on the variable $X_{kk'}^{ihs}$, where $k \in K$ and $k' \in K'$. K is the set {mining, flotation, mine to blend for (j,d), flotation to blend for (j,d)}, where j = 1, ..., J(i) and d is fixed. Thus $X_{kk'}^{ihs}$ may represent the tonnage of region i's (h,s)-grade production experiencing one conversion or conversion sequence from set K followed by shipment to a destination allowed by set K'.

The number of allowable conversion sequences is kept to a minimum in order to minimize the number of variables in the LP. Recall that a cleaned product may be input to a blending process, but not vice-versa; and all conversion is assumed to occur in the region of origin.

Continuing with the indices:

t or t^0 a time period. No effort has been made to find the most efficient planning horizon (number of time periods in the analysis). Most industry and government studies are in terms of goals for 1985 or 1990.[16]

h a heat value range (BTU content) classification. For example, h = 9000 may represent coal with between 8000 and 10,000 BTU/lb.

s a sulfur content range classification, e.g., s = 3 may denote 2.8%-3.2% sulfur content.

e the rate of extraction (production) of a mine, in tons/period.

d the contracted rate of delivery to a customer, in BTU's per period.

τ always occurs in conjunction with d or e; thus signifies the productive lifetime of a mine given extraction rate e; also used for the agreed lifetime of a contract (at delivery rate of d BTU's/period). In periods.

ℓ a transport mode. In the present model, rail or slurry pipeline.

Decision variables are:

$C_{ij}^{\tau d}(t)$ the number of contracts negotiated in period t between region j consumers and region i producers for the delivery of d BTU's per period over a term of τ periods.

$m_i^{hs\tau e}(t)$ the number of mines with potential lifetime output τe, coal of heat value h and sulfur content s, to produce at e tons per period, opening in region i during period t.

$X_{kk'}^{ihs}(t)$ tons of hs-grade coal (heat value class h, sulfur content class s) moving from conversion site(s) $k \in K$ to conversion sites $k' \in K'$ within region i in period t.

$y_{ij}^{\ell}(t)$ total tons of coal moved from region i to region j in period t via transport mode ℓ.

$\phi^i(t)$ number of additional flotation cleaning facilities constructed in region i during period t. An integer.

$\beta^i(t)$ similar for blending facilities in region i.

$\sigma_{ij}^{\ell}(t)$ number of mode ℓ links from i to j constructed in t. An integer.

$Sjd(t) \in \{0,1\} = 1$ if postcombustion scrubbing facilities are to exist for size d consumers in region j, period t.

All conversion, transportation, and scrubbing facilities are assumed to have a productive life time which exceeds the planning horizon. Time delays due to construction may be expressed by summing over appropriate sets of time period indices in the equations below.

Although coal liquefaction and gasification are not mentioned above, those possibilities, as well as more exotic conversion technologies and their supporting transport modes, can be treated directly by the conversion/transport portion of the model as it stands presently. As these conversion modes gain greater economic significance, their inclusion in the model will be justified. Minehead electrification for interregional transmission is easily dealt with as an additional conversion option, with the furnace being subject, of course, to the air standards of the origin region. The inefficiency due to voltage drop over distance would be factored in. Incorporating gasification would be easier because a clean-burning gas would not be subject to air standards. Liquefied coal would presumably have a different market (auto fuel and so forth) than considered here, but it would still be supplied on a volume contract to a distributor and would be subject to emission standards; therefore, it need not be treated differently, except for the addition of feasible transport modes.

The model incorporates the behavioral assumption that the reserves of a region will go to satisfy that region's demand before interregional contracts are considered. A case supporting this assumption is that of Kansas City Power and Light.[17] The company uses local coal at 30% the cost of imported Wyoming coal. The local economy is stimulated by K.C.P. & L.'s policy. (One added cost to the utility, but of benefit for the local region, is that stack scrubbers are needed due to the sulfur level of the local coal.) This assumption is incorporated by arbitrarily setting intraregional transport costs orders of magnitude less than interregional transport costs. In accord with this strategy, no distinction between different mining or blending sites within a region needs to be made. An interregional model of manageable size requires that individual regions be considered points on a plane. In a given application, regions must be defined judiciously, in accord with observable spatial clusters of activity, so as to minimize the effects of the suboptimization. That is, the "intraregional" activity, exogenous to the model, which might, considered as interregional activity between redefined regions, produce a more efficient overall distribution pattern. Similarly, although the general model as formally presented here is complex, particular applications will not involve the full range of options provided, and (because each option considered increases the size of the linear programming problem) the number of indices, variables and constraints will be reduced.

Input to the model includes (1) the detailed costs of each production, conversion, and transportation option as discussed above; (2) the environmental standards and other legislative parameters such as water rights and production quotas for each region and period; (3) the numbers of initially outstanding contracts of each type, by region; (4) the initially existing conversion capacity of each type, by region; (5) natural resource limitations such as coal reserves, and water available for pipelining; and (6) demand projections in the form of demand for each type of contract. Notation and the form of each input will be introduced as the constraints are listed. Summing over indices of $C_{ij}^{\tau d}(t)$ gives other quantities of interest:

$\Sigma_i C_{ij}^{\tau d}(t)$	total new contracts from region j customers in period t, with terms τ, d.
$\Sigma_{t^\circ=1}^{t} \Sigma_i C_{ij}^{\tau d}(t^\circ)$	total such contracts concluded since period 1 by these customers.
$\Sigma_{t^\circ=0}^{t} \Sigma_i \Sigma_{\tau \geq t^\circ} C_{ij}^{\tau d}(t-t^\circ)$	total unexpired contracts in force for region j at t.
$\Sigma_d \Sigma_{t^\circ=0}^{t} \Sigma_{\tau \geq t^\circ} dC_{ij}^{\tau d}(t-t^\circ)$	total shipments (in BTU's) from i to j during t.

and so on.

Prodeeding to the constraints for the LP model:

I. A. Reserves in each region, of each grade of coal, exceed the total eventual output of all mines opened within the horizon in that region, including mines operating initially.

$$\alpha R_i^{hs} \geq \sum_{\tau} \sum_{t=0}^{T} \sum_{e} \tau em_i^{hs\tau e} \quad \forall h,s,i$$

where

e = extraction rate

R_i^{hs} = initial reserves in i of hs-grade coal

α = fraction of reserves which is recoverable. α may be made to vary for different grades, or over time.

B. Mine shipments = rate of output of mines = periodic shipments to storage, to flotation, to blending and directly out of region.

$$\sum_{e} \sum_{t^\circ=0}^{T} \sum_{\tau \geq t-t^\circ} em_i^{hs\tau e}(t^\circ) = \sum_{k' \epsilon K'} X_{kk'}^{ihs}(t) \quad \forall h,s,t,i$$

where

$k \quad = \text{mine},$

$k' \in K' = \{\text{storage; flotation; blend for } j(i),\ d\text{; ship to } j(i),\ d\}$

and $j(i)$ is a region served by contract from i. $j(i)$ ranges from 1 to $J(i)$, and d ranges over all consumption rate classes, in a manner similar to h and s. Note that throughout we allow the possibility $j(i) = i$.

C. Possibly there are upper and lower bounds on construction of mines of each type and size.

$$\underline{B}_i^{hs\tau}(t) \leqq M_i^{hs\tau e} \leqq \overline{B}_i^{hs\tau}(t) \quad \forall i,h,s,\tau,e,t$$

These bounds, when not due to equipment shortages, may be legislative in origin. Strip mining legislation may bound from above the rate of capacity expansion for environmental reasons. On the other hand, companies which hold government coal land leases do so, in many cases, on the basis of a promise to expand production at a given rate.[18]

II. Flotation Cleaning

The sulfur content of a lump of coal has two components: an iron sulfide ("pyrite") admixture, and "organic" sulfur chemically tied to the coal itself.[19] The two types of sulfur comprise roughly equal proportions in most coal. A two stage chemical bath flotation process developed in the early '70s by the Bureau of Mines can remove on the order of 88% of pyritic sulfur.[20] Prior to the development of this process, such "cleaning" procedures could remove only about half the pyritic sulfur.

We assume that a cleaning process conserves mass, i.e. that the process does not lighten the coal and that coal power is not used to drive the process. If relaxing this assumption is desired, an input/output ratio factor can be included in the throughput equation. It is further assumed that it is always economical to remove all the pyritic sulfur that the process is capable of removing, and that this amount is similar for all coal samples of equal initial sulfur content. Thus if x tons of coal with sulfur content s, and removable fraction of sulfur α, is input to the cleaning process, the output will be x tons of coal with sulfur content $(1 - \alpha)s$. Given a set of sulfur content categories s, s', etc., we define $\gamma_{ss'} \varepsilon \{0, 1\}$, with $\gamma_{ss'} = 1$ if s can be cleaned up to s'. Output from flotation can go either directly to the customer or into blending.

A. Throughput

$$\sum_h \gamma_{ss'} \sum_{k \varepsilon K} X_{kk'}^{ihs}(t) = \sum_h \sum_{k'' \varepsilon K''} X_{k'k''}^{ihs'}(t) \quad \forall i,t,s,s'$$

where

K = {mine, storage}

k' = flotation

K'' = {blending for j(i), d,; shipment to j(i), d}

B. Capacity

Let Δ_f = the capacity of a flotation plant. The notation may be extended when a choice of plant sizes exists. Then

$$\sum_h \sum_s X_{kk'}^{ihs}(t) \leq \Delta_f \sum_{t^\circ=0}^{t} \phi^i(t^\circ) \quad \forall i,t$$

where

$\phi^{i}(t^{o})$ is an integer.

III. Blending

The basic presumption is that blending two samples of coal of different sulfur content and heat value yields a product of intermediate sulfur content and heat value.[21]

A. Throughput: The input to the blending process (on the left hand side) is tagged "jd" for its destination region and customer size. This convention makes it possible to produce a distinct blend for each class of customer. Increments in operating costs due to production of multiple blends are ignored.

The sulfur or heat content of the blend is a weighted average of the S or BTU content of the inputs. These identities are used in the formulation of further constraints:

Sulfur content of jd blend =

$\sum_{h} \sum_{s} \sum_{k \varepsilon K} s \, X_{kk'}^{ihs}(t)$, where K = mine, storage, flotation and k = blending for j,d.

BTU content of jd blend

$\sum_{h} \sum_{s} \sum_{k \varepsilon K} h \, S_{kk'}^{ihs}(t)$,

in units of raw tons of sulfur and BTU's, respectively.

B. Capacity: Notation as in II. B.

$$\sum_{h} \sum_{s} \sum_{k \varepsilon K} \sum_{k' \varepsilon K'} X_{kk'}^{ihs}(t) \leqq \Delta_b \sum_{t^\circ=0}^{t} \beta^{i}(t^\circ) \quad \forall i,t$$

with $\beta^{i}(t)$ integer,

K = {mine, storage, flotation}

K' = {blend for j(i), d ; for all j(i), d}

As in the cleaning process, conservation of mass is assumed for blending.

IV. Interperiod Storage

A. Throughput: The cumulative entries since t = 0 into each region's inventory must, at the end of each period, exceed the cumulative withdrawals.

$$\sum_{t^\circ=0}^{t} X_{kk'}^{ihs}(t^\circ) \geqq \sum_{t^\circ=1}^{t} \sum_{k'' \varepsilon K''} X_{k'k''}^{ihs}(t^\circ) \quad \forall\ i,h,s,t$$

where

k = mine

k' = storage

K'' = {flotation; blend for j(i), d; ship to j(i), d}

for all j(i), d.

This constraint allows storage only of uncleaned, unblended product in its region of origin.

B. Capacity:

$$\sum_{h} \sum_{s} \sum_{t^\circ=0}^{t} [X_{kk'}^{ihs}(t^\circ) - \sum_{k'' \varepsilon K''} X_{k'k''}^{ihs}(t^\circ)] \leqq \Delta_s \sum_{t^\circ=0}^{t} \eta^{i}(t^\circ)$$

k,k',K" as above; ∀i,t;

$\eta^i(t)$ = number of storage sites added at i in t

Δ_s = capacity of storage site.

This representation of the inventory process is, of course, a very rough approximation because the time periods considered are long and the amount of coal in storage at a given moment will vary.

V. Interregional Shipments = cumulative contract commitments for current shipment, expressed in BTU's = BTU's shipped direct from mine, storage, or flotation, plus BTU's in blended product shipped.

$$\sum_{t^\circ=0}^{t} \sum_{\tau \geqq t-t^\circ} dc_{ij}^{\tau d}(t^\circ) = \sum_{h} \sum_{s} h \sum_{k \varepsilon K} \sum_{k' \varepsilon K'} x_{kk'}^{ihs}(t) \qquad \forall i,j,t,d$$

Here, K = {mine; mine/blend for j, d,; flotation; flotation/blend for j,d; storage; storage/flotation/ storage/blend for j,d; storage/flotation/blend for j,d}

K' = {shipment to j, d}.

Note that there is a separate equation for each (j,d) pair within each i and t. In these constraints, K includes all possible sequences of pre-shipment conversions.

VI. Transportation

This section refers to and depends on the development of the "contract network flow problem" presented in the Appendix.

Let $\mu^{\ell}(t)$ be the a priori permissible incidence matrix of the transportation network with respect to mode ℓ for period t. That is, $\mu^{\ell}_{ij}(t) \epsilon \{0, 1\}$ is positive if it is expected that a mode ℓ link from region i to region j will be possible in period t. These matrices will in general not be symmetric--a pipeline, for example, allows flows in one direction only.

Defining K and K' as in section V, the total actual tonnage committed from region i to region j in period t is $\sum_d \sum_h \sum_s \sum_{k \epsilon K'} X^{ihs}_{kk'}(t)$, where the j subscript appears within the definition of K'. For the sake of compact notation, let us call this quantity $C_{ij}(t)$, and use it in the flow equations below.

A. 1. Kirchoff equations

a. Supply

$$\sum_j C_{ij}(t) - \sum_i \mu^{\ell}_{ij}(t) y^{\ell}_{ij}(t) + \sum_i \mu^{\ell}_{ji}(t) y^{\ell}_{ji}(t) = 0$$

$\forall$ region i, mode ℓ, period t.

b. Demand

$$\sum_i C_{ij}(t) + \sum_i \mu^{\ell}_{ij}(t) y^{\ell}_{ij}(t) + - \sum_i \mu^{\ell}_{ji} y^{\ell}_{ji}(t) = 0$$

$\forall i, \ell, t.$

2. Lower bounds and generalized lower bounds on $y^{\ell}_{ij}(t)$ as set forth in Appendix.

B. Mode Capacities

1. Mode construction

$$Y_{ij}^{\ell}(t) \leqq \Delta^{\ell} \sum_{t^{\circ}=0}^{t} \sigma_{ij}^{\ell}(t^{\circ}) \qquad \forall \ell, i, j, t$$

with

Δ^{ℓ} = capacity of a single mode ℓ line, e.g. a single pipeline or rail link

$\sigma_{ij}^{\ell}(t)$ = number of additional mode ℓ links from i to j constructed in period t.

2. Bounds on construction

$$\underline{\sigma}_{ij}^{\ell}(t) \leqq \sigma_{ij}^{\ell}(t) \leqq \bar{\sigma}_{ij}^{\ell}(t) \quad \text{where appropriate.}$$

These bounds may be due to legislation or currently existing commitments to construction.

3. Natural Resource Limitations on shipments

$$Y_{ij}^{\ell}(t) \leqq L_{ij}^{\ell}(t) \quad \text{where appropriate,}$$

where $L_{ij}^{\ell}(t)$ is imposed by the economic or natural environment. For rail, this parameter may represent limited availability of rolling stock or right-of-way; for pipelines the limitation may be a water shortage in the region of origin, or environmental legislation.

VII. Sulfur Standards

Again we retain the definitions of K and K' from section V.

A consuming region j has the options of constructing and operating postcombustion scrubbers at any time, or operating without stack scrubbers.

In either case, emissions must satisfy the regional standard for furnaces of that size and year:

A. Unscrubbed:

$$\sum_{i} \sum_{h} \sum_{s} \sum_{k \varepsilon K} sx_{kk'}^{ihs} (t) \leqq Q_{jd} (t) + M \cdot \sum_{t^\circ = 0}^{t} S_{jd}(t^\circ)$$

$$\forall j,d,t$$

where $S_{jd}(t) \varepsilon \{0, 1\}$ and is positive if scrubbers are to be used by d-size plants in j beginning in period t; where $Q_{jd}(t)$ is the current regional standard for size d plants, in raw pounds of sulfur per period; M is a very large positive number; and we have expressed the blending output in terms of the input to blend in order to keep track of the sulfur content. The constraint states that the effluent from a furnace without a stack scrubber (this would be the entire sulfur content of the fuel input) must meet the air standard.

Constraint VII. B. covers the case of furnaces with stack scrubbers. The scrubbed effluent must again satisfy the air standard, having had (we shall assume) a fraction F of its sulfur dioxide content removed by the scrubber. The Bureau of Mines' 4-stage citrate scrubbing process can be operated for about $4.10/ton of coal burned, not counting profits from sale of recovered sulfur.[22] In this process, the waste gas is washed to remove sulfur trioxide. Remaining sulfur dioxide is absorbed in a citric acid solution, where it reacts with hydrogen sulfide to produce elemental sulfur. This product is then separated from the solution.

B. Scrubbed:

$$(1 - F) \sum_i \sum_h \sum_s \sum_{k \varepsilon K} sx_{kk'}^{ihs}(t) \leqq Q_{jd}(t)$$

C. Scrubbing "infrastructure": stack scrubbers need be constructed only once at a given plant.

$$\sum_{t^\circ=0}^{t} S_{jd}(t) \leqq 1 \qquad \forall j,d$$

D. Bounds on scrubber construction: scrubbers may be compulsory (see page 2).

$$\underline{S}_{jd}(t) \leqq S_{jd}(t) \qquad \text{where appropriate}$$

VIII. Demand

$C_j^d(t)$, the projected demand for τd-type contracts in each region and period, is a scenario parameter.

$$\sum_i C_{ij}^{\tau d}(t) = C_j^{\tau d}(t) \quad \forall t,j,\tau,d$$

IX. Nonnegativity of all variables.

Figures for the fixed and variable costs of mining, flotation cleaning, blending, stack scrubbing, rail and pipeline transportation, intermodal transfer, storage, and administration of contracts may be associated with their respective activity variables for use in a cost-minimizing or costmeasuring model. We have followed this course in the computational examples mentioned.

A Computed Example

Four hypothetical regions, roughly approximating four multistate regions in the Midwestern and Western United States, were posited for the purpose of a small computed example. Two of these regions were exclusively exporters while the remaining two were exclusively importers, although all regions were coal producers. (Each importing region's demand exceeded its own production.) Coal was classified as "low sulfur/low BTU" or "high sulfur/high BTU" for the purposes of this simple example. The latter could be converted to "low sulfur/high BTU" via flotation or suitable blending. Transportation was by rail or pipeline, with some bounds on pipeline flow due to Western water shortages. Two five-year planning periods were used, and all mines and customers were of a uniform size. Mines and contracts were both to endure fifteen years, with mines producing on the order of 500,000 tons/year, and customers requiring 4.5×10^{13} BTU's per period per contract. The remaining parameters of the model, including costs, initial facilities, reserves, and demands, were approximated on an order-of-magnitude basis by inspection of the literature cited earlier.

The linear programming problem, amounting to 144 columns and 80 rows, was solved in 15 seconds via the LP6600 code at the Center for Cybernetic Studies of the University of Texas at Austin on the University's CDC 6600/6400 computer system. Runs were repeated under various values of parameters. Each case that yielded an optimal solution involved heavy usage of blending rather than cleaning and dependence on a pipeline transport rather than rail. Broad conclusions should not, however, be drawn on the basis of this limited experimentation.

Conclusions: Energy Policy, Supply, and Location Decisions

The production-distribution model presented here seems sufficiently comprehensive to encompass, either directly or approximately, the most important factors which, judging from current events, will constrain the coal industry in years to come.[23] The model is on the other hand compact enough to be computationally economical.

As implied earlier, some extensions to the model eventually may be desired. These would include contract renegotiation and a more explicit treatment of competitive effects. Also deserving of inclusion are an interface with the financing function and an investigation of the role of coal in the United States' international trade.

The energy issue will have a potentially enormous impact on the location decisions of manufacturers. Future energy policies will have a major effect on the spatial arrangements of (a) oil wells, coal mines, refineries, transportation routes, and intermodal transfer facilities, (b) manufacturers of equipment for the generation of electricity, and (c) energy-intensive industries requiring a reliable power source.

The preferred locations of these activities are ever-changing, as they exist within a vicious circle tied to the general economy: production cutbacks in times of sluggish economy reduce energy demand, therefore reducing the funds available for expansion of generating capacity. Orders for electrical generating equipment are postponed or canceled, and the movement of new industrial plants into the area, which would stimulate the local economy, is discouraged due to the insecure future power supply.[24]

The linear programming model described herein is intended to assist the formulation of location decisions relating to the distribution of the primary fuel. The location decisions of industries with intensive input-output relationships to users of the primary fuel are closely related but external to the results of the LP model. As such, some of the implications of energy policy for these industries should be noted.

Industries which are heavy users of electrical power face a supply problem that can be qualitatively different from supply problems associated with material production inputs. Except for plants which can maintain an adequate backup power system, there is no production inventory of electricity and the production process must endure an occasional brownout. However, many industries--for example those involving life-support systems for organisms or constant temperatures for chemical or electronic processes--require an absolutely stable energy input. Brownouts are unacceptable not only now, but over the projected life of the plant. An example of industrial migration resulting from a constant energy requirement is the movement of silicon-related processes away from the San Francisco Bay region. Intel, a manufacturer of silicon wafers, must cool the tubes surrounding the finished wafers from 1100° C, on a 24-hour time-temperature curve, to prevent shattering. In case of a brownout, the rare tubes would have to be replaced and the furnaces rebuilt. For this reason, Intel has moved its plant to Oregon's Columbia River, where the power is abundant. A company spokesman says, "If a black-out hit Silicon Valley (California), there aren't enough diffusion tubes in the world to refit in less than three to four months. The consequences for . . . (for example) the automobile industry, are incalculable."[25]

In more conventional industries, the need for secure energy supply is also obvious. The Detroit area provides some recent examples. North Star Steel of St. Paul found southeastern Michigan an ideal environment for a new mill in all respects of supply and market--except power.[26] The two major Detroit utilities were unable to convince North Star or its location consultant that the long-term power picture would be stable. Detroit Edison's top planning executive predicts brownouts or worse by 1980 with services continuing to deteriorate thereafter. Detroit Edison's expansion plans, as of May 1975, were stymied due to lack of capital in exactly the manner described earlier. The situation has not only blocked the incursion of North Star and other large companies into the Detroit area, but also is alienating established local industry as well--General Motors is hedging its power supply problems by developing natural gas resources on G.M. land in Ohio, despite legal battles over possible public ownership of the gas, and another of the Big Three auto manufacturers plans no further plant construction in Michigan unless the electric and gas supply picture improves.

Companies which supply utilities with equipment are experiencing increased uncertaintly. Westinghouse and General Electric, in the face of cutbacks and cancellation on orders for gas turbines, have ceased producing for stock.[27] Production is now on an order-only basis, and then only after a waiting period to see whether the order "holds up." The resulting production cutback has forced the closing of the Westinghouse Round Rock turbine plant near Austin, Texas and has increased the lead time on new turbine orders.

There is also evidence that large industries will abandon the utilities in favor of integrating power supply sources into their production processes. G.E. has, a spokesman said, been "shifting away from domestic utility orders to . . . smaller (turbine) units for industrial, petrochemical, and international customers."[28] A decoupling of utilities and manufacturers would of course alter the location planning process, and possibly the actual location decisions for industry.

APPENDIX

THE CONTRACT NETWORK FLOW PROBLEM

The body of this report describes a linear programming problem, part of which involves determining the optimal movements of coal through a transportation network in which individual regions correspond to the nodes of the network. Each node is exclusively a source or sink, although transshipment is possible through any node. Supplies at the source nodes and demand at the sink nodes are respectively the current commitments associated with all "outward" and "inward" contracts binding the producers and consumers at those nodes.

The ordinary transshipment problem would consist of assigning least-cost flows along each arc, respecting this aggregate supply-demand structure. But in the present case, the contract commitments between pairs of nodes are also known and must be respected. This appendix develops a representation of this problem for inclusion in the coal distribution model, and also suggests that the "contract network flow problem" is worth investigation as a special network structure.

In a recent article, Charnes and Cooper trace the techniques of operations research and managerial economics from their initial military environment, through later small-scale applications within the private firm and still later comprehensive planning roles in the corporation, to recent incursions into the public sector in a problem environment of multiple entities pursuing conflicting goals.[29] Each phase is shown to have its own types of problems, requiring adaptations of modelling methods. This evolutionary trend may explain why the problem of network flows under contracts, a fairly straightforward idea, has not been addressed earlier--the problem would not arise explicitly in single-firm applications.

An example will help to develop notation:

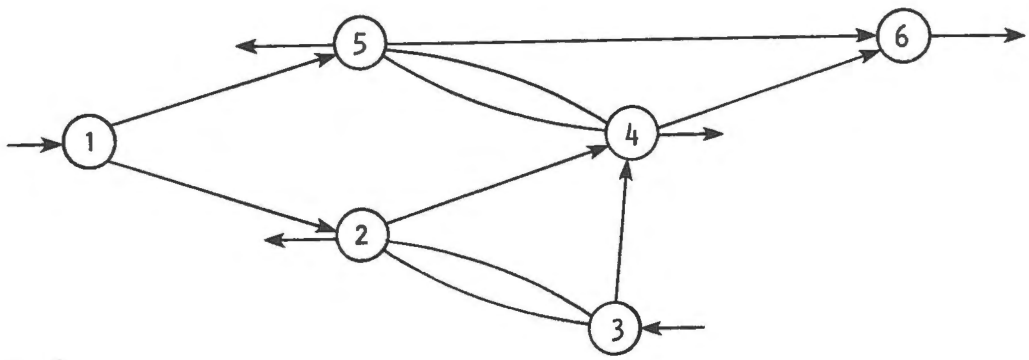


Figure 2.1

There may be reasons for excluding, a priori, certain paths between any pair of nodes. Judgment of political and economic feasibility of the network leads to a set of permissible paths between each pair of nodes. For example, referring to Figure 2.1, the following sets of paths emerge.

Table 2.1

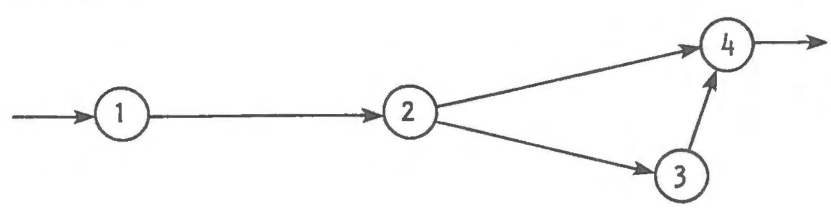
A Set of Permissible Paths from Network 2.1

sinks / sources	2	4	5	6
1	(1,2)	(1,2,4) (1,2,3,4)	(1,5)	(1,5,6) (1,2,4,6) (1,5,4,6)
3	(3,2)	(3,4)	(3,4,5)	(3,4,6) (3,4,5,6)

Each cell of Table 2.1 contains a set of paths which form a directed subnetwork of network 2.1. Considering the subnetwork associated with source i and sink j, we see that constraints are required which assure a flow of at least C_{ij} units over the subnetwork, where C_{ij} is the volume committed to j and from i. The constraints take the form of lower bounds on the flows across sets of arcs of the subnetwork.

For example, given a contract between supplies in mode 1 and consumers in node 4, we have

Subnetwork 1-4:



Clearly, we must have $X_{12} \geqq C_{14}$ and $X_{14} + X_{34} \geqq C_{14}$, where X_{ij} is the flow along arc (i, j). We know, however, that in network 2.1 node 2 is a sink. We do not want flows from 1 which are committed to 4 to be drawn off by the sink at 2--therefore we must further specify $X_{24} + X_{23} \geqq X_{12}$ and $X_{34} \geqq X_{23}$

Continuing in this fashion for all subnetworks i-j:

1 - 2:	$X_{12} \geqq C_{12}$	
1 - 4:	$X_{12} \geqq C_{14}$	$X_{24} + X_{23} \geqq X_{12}$
	$X_{24} + X_{34} \geqq C_{14}$	$X_{34} \geqq X_{23}$
1 - 5:	$X_{15} \geqq C_{15}$	
1 - 6:	$X_{12} + X_{15} \geqq C_{16}$	$X_{24} \geqq X_{12}$
	$X_{56} + X_{46} \geqq C_{16}$	$X_{56} + X_{54} \geqq X_{15}$
		$X_{46} \geqq X_{24} + X_{54}$
3 - 2:	$X_{32} \geqq C_{32}$	
3 - 4:	$X_{34} \geqq C_{34}$	
3 - 5:	$X_{34} \geqq C_{35}$	
	$X_{45} \geqq C_{35}$	
3 - 6:	$X_{34} \geqq C_{36}$	$X_{45} + X_{46} \geqq X_{34}$
	$X_{46} + X_{56} \geqq C_{36}$	$X_{56} \geqq X_{45}$

For each contract-bound source-sink pair, then, we have two sets of inequalities. The first group requires that the immediate flows from the source i and the immediate flows to the sink j must each exceed C_{ij}; the second group provides that the volume out of each intermediate node is at least as large as the volume in.

Note that the constraints for the various subnetworks often show identical or similar left-hand sides. In the former case, clearly, the set of arcs must carry the total flow assigned by all subnetworks. If the left-hand side of one constraint comprises a term of the left hand side of another constraint, the right-hand side of the latter must be augmented accordingly. For example, if $X_{78} \geqq C_{78}$ and $X_{78} + X_{89} \geqq C_{69}$, it follows that we must replace the latter constraint by $X_{78} + X_{89} \geqq C_{69} + C_{78}$.

To illustrate, we consolidate the above set of constraints, eliminating redundancies:

$$X_{12} \geqq C_{14} + C_{12}$$

$$X_{34} \geqq C_{34} + C_{35} + C_{36}$$

$$X_{15} \geqq C_{15}$$

$$X_{32} \geqq C_{32}$$

$$X_{45} \geqq C_{35}$$

(R) $X_{12} + X_{15} \geqq C_{16} + (C_{15}) + (C_{14} + C_{12}) = \sum_j C_{1j}$

$$X_{24} + X_{34} \geqq C_{14} + (C_{34} + C_{35} + C_{36})$$

(R) $X_{46} + X_{56} \geqq C_{16} + C_{36} = \sum_i C_{i6}$

$$X_{34} \geqq X_{23}$$

$$X_{24} \geqq X_{12}$$

$$X_{56} + X_{54} \geqq X_{15}$$

$$X_{46} \geqq X_{24} + X_{54}$$

$$X_{45} + X_{46} \geqq X_{34}$$

$$X_{56} \geqq X_{45}$$

It remains to write the ordinary Kirchoff node constraints for the whole network 2.1. As we do so, the inequalities marked (R) above are seen to be redundant.

$$\sum_j C_{1j} = X_{12} + X_{15}$$

$$\sum_j C_{3j} = X_{32} + X_{34} - X_{23}$$

$$\sum_i C_{i2} = X_{12} + X_{32} - X_{24} - X_{23}$$

$$\sum_i C_{i4} = X_{54} + X_{24} + X_{34} - X_{45} - X_{46}$$

$$\sum_i C_{i5} = X_{15} + X_{45} + X_{54} - X_{56}$$

$$\sum_i C_{i6} = X_{56} + X_{46}$$

and $X_{ij} \geqq 0$ for all i, j

To summarize, the specification of the contract network requires these steps:

(1) specify all i - j subnetworks, where i is a source and j a sink.

(2) consolidate these inequalities into a set of lower-bound and generalized-lower-bound inequalities whose right-hand sides are sums of the right-hand sides of the individual subnetwork constraints.

(3) include the ordinary transshipment equations for the network as a whole.

(4) eliminate redundancies.

The additional constraints on the network due to contracts are thus of three types: lower bounds, generalized lower bounds, and inequalities whose left-hand sides reappear as terms in the overall Kirchoff node equations. These regularities suggest the possibility of a fast special-purpose algorithm for the contract network flow problem.

For the present application, the contract network is embedded in a larger linear programming problem. However, other applications seem feasible. For example it may be desired to minimize traffic congestion in a city district where wholesalers, bakeries, and butchers regularly deliver goods to certain restaurants at a particular time of day.

ENDNOTES

[1] A. Charnes, W. W. Cooper, and M. H. Miller, "Application of Linear Programming to Financial Budgeting and the Costing of Funds," Journal of Business of the University of Chicago, 22, No. 1 (1959).

[2] Editorial, Coal Age, 80, No. 1 (Jan., 1975), p. 53.

[3] Letter received from Wallace W. Wilson, August, 1976.

[4] Barry Commoner, The Poverty of Power (New York: Alfred A. Knopf, Inc., 1976).

[5] OECD, Problems and Prospects in the Coking Industry in the OECD Countries (Paris: OECD, 1972) and A. Ravindran, R. E. Bailey, and D. L. Hanline, "A Feasibility Study of Coal Precombustion Processing--An Operations Research Application," 27th Annual Conference of the American Institute of Industrial Engineers, St. Louis, May, 1976.

[6] National Coal Association, 1974-75 Coal Facts (Washington, D.C.: N.C.A.).

[7] National Coal Association, 1974-74 Coal Facts.

[8] A. Ravindran, R. E. Bailey, and D. L. Hanline.

[9] A. J. Mayer and William J. Cook, "The Only Way to Use Coal," Newsweek, 4 July 1977 and National Coal Association, 1974-75 Coal Facts.

[10] National Coal Association, 1974-75 Coal Facts.

[11] A. Ravindran, R. E. Bailey, and D. L. Hanline.

[12] A. Ravindran, R. E. Bailey, and D. L. Hanline.

[13] Editors of Coal Week, Fuel Price Analysis (New York: McGraw Hill, Monthly) and National Coal Association, Keystone Coal Industry Manual (New York: McGraw Hill, 1974).

[14] J. E. Hass, E. J. Mitchell, and B. K. Stone, Financing the Energy Industry (Cambridge, Mass.: Ballinger Publishing Co., 1974) and P.C. Merritt, "Project Financing: Customized Money Packages for Coal Mine Development--An Interview with Continental Illinois' Wallace W. Wilson," Coal Age, 80 (April, 1975), p. 98.

[15] A. M. Geoffrion and G. W. Graves, "Multi-Commodity Distribution System Design by Benders Decomposition," Management Science, 20, No. 5 (Jan., 1974).

[16] U.S. Dept. of Commerce, Commerce Technical Advisory Board, C.T.A.B. Recommendations for a National Energy Program (Washington, D.C.: GPO, March, 1975).

[17] George Getschow, "Coal Cleanup," The Wall Street Journal, 14 June 1977.

[18] "Marketing Appalachian Coal," Coal Age, 80 (Mid-May, 1975).

[19] National Coal Association, Keystone Coal Industry Manual.

[20] National Coal Association, Keystone Coal Industry Manual, p. 213.

[21] An MILP model for location of blending facilities in Indiana is presented by A. Ravindran (A. Ravindran, R. E. Bailey, and D. L. Hanline).

The blending problem was first cast in LP form in the context of the petroleum industry by A. Charnes, W. W. Cooper, and B. Mellon (A. Charnes, W. W. Cooper, and B. Mellon, "Blending Aviation Gasolines--A Study in Programming Interdependent Activities," Econometrica, 20, No. 2 (April, 1952), pp. 135-159.).

[22] A. Ravindran, R. E. Bailey, and D. L. Hanline.

[23] The August, 1977 Texas Monthly discusses legal questions of eminent domain as relating to pipeline companies and the resulting conflict with railroad interests. An interregional pipeline must, of course, cross several railroad rights-of-way. The Wall Street Journal, 8 August 1977. reporting on President Carter's energy plan, details exemptions and partial exemptions from compulsory scrubbing for plants of differing size. Both of the above factors are easily accommodated by the present model.

[24] E. Rubinstein, "Cash Crunch: Its Ripple Effect," I.E.E.E. Spectrum (May, 1975), p. 41 and "Utilities: Weak Point in the Energy Future," Business Week, 20 (Jan., 1975).

[25] E. Rubenstein, p. 41.

[26] E. Rubenstein, p. 41.

[27] E. Rubenstein, p. 41.

[28] E. Rubenstein, p. 41.

[29] A. Charnes and W. W. Cooper, "Managerial Economics--Past, Present, and Future," research report CCS 287, Center for Cybernetic Studies, University of Texas at Austin (1977).

BIBLIOGRAPHY

Auerbach, W. "Money Managers Eye the Future of Coal." Coal Age, 80, No. 1 (Jan., 1975).

Bankers Trust Co. "Capital Resources for Energy through the Year 1990." 1976.

Buck, P., and N. Savage. "Determine Unit Train Requirements." Power, Jan. 1974; reprinted in Keystone Coal and Industry Manual, 1974.

Charnes, A., W. W. Cooper, and B. Mellon. "Blending Aviation Gasolines--A Study in Programming Interdependent Activities." Econometrica, 20, No. 2 (April, 1952).

Charnes, A., W. W. Cooper, and M. H. Miller. "Application of Linear Programming to Financial Budgeting and the Costing of Funds." Journal of Business of the University of Chicago, 32, No. 1 (1959).

"Marketing Appalachian Coal." Coal Age, 80 (Mid-May, 1975).

Editorial. Coal Age, 80, No. 1,(Jan., 1975).

Editors of Coal Week. Fuel Price Analysis. New York: McGraw-Hill, monthly.

Commoner, Barry. The Poverty of Power: Energy and the Economic Crisis. New York: Alfred A. Knopf, Inc., 1976.

Cooper, H. G. H., Jr. "Environmental and Energy Impacts of Coal Energy Transshipment through Railroad Electrification." working paper, Council for Advanced Transportation Studies, University of Texas at Austin, April, 1975.

Forbes. 15 Dec. 1975.

Friedlander, G. F. "Energy's Hazy Future." IEEE Spectrum (May, 1975),

Geoffrion, A. M. "A Guide to Computer Assisted Methods for Distribution Systems Planning." Sloan Management Review (Winter 1975).

Geoffrion, A. M. and G. W. Graves. "Multi-Commodity Distribution System Design by Benders Decomposition." Management Science, 20, No. 5 (Jan., 1974).

Getschow, George. "Coal Cleanup." The Wall Street Journal, 14 June 1977.

Goodridge, E. R. "BLM proposal will Tighten Requirements of Federal Coal." Coal Age 80, No. 1, (Jan., 1975).

Hass, J. E., E. J. Mitchell, and B. K. Stone. Financing the Energy Industry. Cambridge, Mass.: Ballinger Publishing Co., 1974.

Hudson, Edward A. and D. W. Jorgenson. "U.S. Energy Policy and Economic Growth, 1975-2000." Bell Journal of Economics and Management Science (Autumn 1974).

Knight, Kenneth E., George Kozmetsky, and Helen R. Baca. Industry Views of the Role of the Federal Government in Industrial Innovation. Graduate School of Business, The University of Texas at Austin, 1976.

Levesque, R. "Viability of Western Coal in Eastern Markets: An Overview Study for the General Energy Corporation," Vol. I, Midwest Research Institute Report 3996-D. Kansas City, Mo.: M.R.I., October, 1974.

Mayer, A. J. and Cook, W. J. "The Only Way to Use Coal." Newsweek, 4 July 1977.

Merritt, P. C. "Project Financing: Customized Money Packages for Coal Mine Development--An Interview with Continental Illinois' Wallace W. Wilson." Coal Age, 80 (April, 1975).

National Coal Association. Keystone Coal Industry Manual. New York: McGraw-Hill, 1974.

National Coal Association. 1974-75 Coal Facts. Washington, D.C.: N.C.A.

National Petroleum Council. "Coal Availability." 1973.

Newsweek 31 Jan. 1977 .

Newsweek 28 Feb. 1977 .

OECD. Problems and Prospects in the Coking Industry in the OECD Countries. Paris: OECD, 1972.

Secretary General of OECD. Energy Prospects to 1985, Vol. II. Paris: OECD, 1974.

Ouellette, R. P. Coal: The Black Magic. MacLean, Va.: The Mitre Corp., 1972.

Ravindran, A., R. E. Bailey, and D. L. Hanline. "A Feasibility Study of Coal Precombustion Processing--An Operations Research Application." 27th Annual Conference of American Inst. of Industrial Engineers, St. Louis. May, 1976.

Rubinstein, E. "Cash Crunch: Its Ripple Effect." IEEE Sprectrum (May, 1975).

Sandoval, A. David. "Regional Impacts of Alternative Energy Policies." discussion paper, Office of Economic Impact, Federal Energy Administration, February, 1975.

U.S. Dept. of Commerce. Commerce Technical Advisory Board. CTAB Recommendations for a National Energy Program. Washington, D.C.: GPO, March, 1975.

"Utilities: Weak Point in the Energy Future." Business Week, 20 Jan. 1975.

Wilson, Wallace W. Letter to author. August, 1975.

Haynes, Kingsley, Jared Hazleton, Tom Kleeman, Fred Phillips, Michael Ryan, and Gerald White. Establishment of Operational Guidelines for Texas Coastal Zone Management. Lyndon Baines Johnson School of Public Affairs, Austin, Texas, 1974.